New Approach to Estimation of Natural and Anthropogenic Components in the Modern Tendencies of Changes of Erosion Intensity and Suspended Sediment Yield in River Basins

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Abstract

The offered approach is based on establishment of functional dependence between river water discharge (Q) and suspended sediment yield (R) ($R = k \times Q^m$, where k and m are empirical coefficients, characteristic for concrete river basin) for the earliest period in a number of observations, which noticeably differs in average sizes of R from subsequent allocated period (or periods). The earliest period is conditionally accepted as "pattern" (model), with which average amount of suspended sediment yield of subsequent period (or periods) is compared. The anthropogenic component during the subsequent period (or periods) is difference between an actual suspended sediment yield and that its hypothetical amount, connected only with changes of natural (mainly, hydro-climatic) factors without any anthropogenic changes of geographical (erosive) conditions in a river basin and calculated by extrapolation for this period (or periods) an early established dependence $R = k \times Q^m$.

1 Introduction

Among methods of estimation of modern spatial changeability of erosion intensity the analysis of river suspended sediment yield (SSY) acts as one of most objective and exact methods, and its results are most representative for global level of studying [1–7, etc.]. At the same time, SSY is not used as absolute measure of erosion intensity in river basin because a considerable part of erosion products is not taken out for its borders by river waters and accumulates on the carrying out ways (the channels, floodplains and slopes), forming the new generations of alluvium, deluvium and proluvium. A portion of these deposits is various, depending on geologic, geomorphic, landscape conditions and cannot be reliably quantitatively defined even for the small river basins; therefore the SSY-analysis is a method of relative estimation of erosion intensity (speaking wider – mechanical denudation) in river basins.

Along with an estimation of spatial changeability, SSY is used for characteristic of temporal variability of erosion, because the SSY-changes for concrete interval of time in any river basin, as whole, are adequate to changes of intensity of given geomorphic process here in same terms. One of directions of studying of temporal variability of erosion on SSY-changes is definition and analysis of modern long-term tendencies. The key problem of the analysis is partition of such tendencies on natural and anthropogenic components. An account of anthropogenic component is important for development and estimation of efficiency of complex actions aimed to decrease of man-caused erosion and reduction of SSY, normal functioning of river systems and hydraulic engineering constructions in them. The works known in world practice in this direction are individual and narrowly regional [8, 9, etc.].

2 Essence of the offered methodical approach

A revealing of tendencies of changes of erosion intensity and SSY in long-term series of observations and also their partition on natural and anthropogenic components are spent to some stages.

1. Combined graphic construction of long-term series of annual SSY and water discharge for analyzed river is carried out.

2. A revealing of linear (an equation of kind R_i (or Q_i) = $\alpha \times t_i + \beta$, where R_i (or Q_i) is theoretical (regressive) amount of SSY(or water discharge) for a year observations t_i, α and β are empirical coefficients of equation) and nonlinear polynomial of sixth degree (an equation of kind R_i (or Q_i) = $\alpha_1 \times t_i + \alpha_2 \times t_i^2 + \alpha_3 \times t_i^3 + \alpha_4 \times t_i^4 + \alpha_5 \times t_i^5 + \alpha_6 \times t_i^6 + \beta$, where α_1, α_2, α_3, α_4, α_5, α_6 and β are empirical coefficients of equation) trends in long-term series of observations for SSY and water discharge. If the linear trend and its equation allow to reveal a general orientation and rates of directed changes of SSY and water discharge, then the polynomial trend of sixth degree as more approached to initial amounts of actual SSY (or water discharge) reflects not only its orientation, but also a "plasticity" of its temporal changeability, allowing to allocate within SSY and water discharge series the periods, which considerably different both average amounts of SSY (or water discharge), and variability of its annual amounts. An application of the polynomial trends with degree more than six does not significantly change, as a rule, a picture of allocated periods and consequently is not expedient. A statistical importance of received equations of regress (trends) is checked by standard procedure by using of Fisher's ***F***-criterion. Construction of the cumulative curves, showing "critical" years of erosion processes development and SSY-dynamics, is also informative [7].

3. Allocation on a basis of visually-graphic analysis of course of polynomial and cumulative curves the periods (as a rule, two or three) with various average amounts and dynamics of SSY is spent; calculation of average amounts with confidential intervals (at 95 %-s' confidential probability), coefficient of variation of annual SSY and water discharge amounts, coefficients of linear determination of SSY concerning a variability of water discharge, coefficient of linear correlation between annual SSY and water discharge sizes for each period. A statistical importance of the specified coefficients is checked by using of Student’s ***t***-criterion and Fisher's ***F***-criterion.

4. Definition of natural and anthropogenic components in the modern tendencies of SSY-changes by following sub-stages:

4.1. A first, early of allocated periods (T_1) is "pattern", concerning which a comparison of characteristics of other, later period(s) of long-term series of SSY (T_2 and, if it is necessity, T_3) is spent. The average characteristics and variability of annual SSY-amounts in period T_1 reflect the developed natural or natural-anthropogenic conditions in river basins before and during a beginning of period, which influenced on sediment transporting ability of river streams. According to N.I.Makkaveev [11], the functional equation of sediment yield (R_i) has following general view:

$$R_i = (A_{er} \times I) \times Q_i^m, \tag{1}$$

where I is a river stream slope, Q_i is an average water discharge of concrete interval of observation (for example, year), A_{er} is complex erosion coefficient, depending on non-uniformity of runoff (water discharge), character of breeds, composing a channel, quantity and size of suspended deposits delivered by tributaries, rain and melted waters and by slope geomorphic processes. The coefficients A_{er} and I can essentially vary from basin to basin depending on local features of denudation, its geologic and geomorphic structure and geographical conditions. In according to exponent m the connection between SSY and water discharge of plain rivers is usually close to square, of mountain rivers – to cubic [12].

Actually, the equation of N.I. Makkaveev (1) is known mathematical equation of kind $y = k \times x^m$, where complex coefficient $k = a \times (A_{er} \times I)$ for all period of observations in some tens years is conventionally constant, concerning a river hydrological post (a is an transitive index depending on dimension of expression of R and Q). This convention is connected by that variability of hydro-meteorological elements from year to year (a quantity and regime of precipitations, degree of soil and ground freezing, intensity of snow-melting, etc.) can certainly to affect on non-uniformity of runoff (water discharge), character and size of suspended deposits, composing the integrated coefficient ($A_{эр} \times I$). By construction of a graph of exponential dependence between SSY and water discharge for period T_1 for each river basin the coefficient $k = a \times (A_{er} \times I)$ and degree m are empirically defined.

4.2. ***Definition of natural (hydro-climatic) component in tendencies of SSY-change.*** If any anthropogenic changes of geographical conditions within a river basin (it can be primary both natural, and already agriculturally transformed landscapes) during the periods following after period T_1 (T_2 and T_3) are absence, then an inter-annual variability of river SSY is defined, basically, by variability of runoff in same temporal interval on the equation (1) received for period T_1, as the integrated coefficient ($A_{er} \times I$) of period T_1 could be extrapolated for periods T_2 (and/or T_3). For received thus some hypothetical hydro-climatically caused annual amounts of SSY – $r_i = f(Q_i^m)$ – of periods T_2 (and T_3) the average long-term values ($r_{av}(T_2)$ or $r_{av}(T_3)$), which are compared with actual average amount of SSY of "pattern" period T_1 – R_{av} (T_1), can be estimated by equation (2). A difference between these averages – Δr (T_2 or T_2), expressed by equation (3), is ***potential hydro-climatically caused change of SSY*** from period T_1 to period T_2 (and/or T_3).

$$r_{av}\ (T_2 \text{ or } T_3) = [\sum r_i\ (T_2 \text{ or } T_3)]/n, \qquad (2)$$

where n is quantity of observation years in period T_2 (or T_3);

$$\Delta r\ (T_2 \text{ or } T_3) = r_{av}\ (T_2 \text{ or } T_3) - R_{av}(T_1) \qquad (3)$$

A sign before Δr specifies to increase ($\Delta r > 0$) or to reduction ($\Delta r < 0$) of potential hydro-climatically caused annual amounts of SSY during the period T_2 (and T_3) in comparison with actual SSY-amounts of period T_1.

However the natural component in variability of erosion processes and SSY is not limited by only hydro-climatic dynamics. A tectonic factor can influence as well. Its role increases with increase of duration of observations for these processes (at least about several centuries). In short numbers of observations (some tens years) only fast displays of this factor can interfere with inter-annual variability of SSY (especially within the small river basins): earthquakes and effusive magmatizm, an influence of wich is limited by mainly mountain territories. As a rule, these displays are expressed in abnormal speeds of mechanical denudation and sizes of SSY. It is quite obvious that an account of tectonic component of SSY-changes is obligatory, for this purpose a working out of special methods of estimation of influence of the factor on SSY and careful monitoring for it are required.

4.3. *Definition of anthropogenic component in tendencies of SSY-changes.* A human activity differently influences on erosion intensity and river SSY in various regions of the Earth. If in the some regions an active human influence on systems of erosion and accumulation and SSY has come to end in the previous centuries, then in other regions it went during the second half of XX-th century and goes nowadays [14]. Allocating an anthropogenic component, it is necessary to understand, what a factor-agent of erosion and formation of river SSY is an natural process – runoff; a human activity as one of factors most dynamically varying in time, only creates or expands the favorable or adverse conditions for its erosion work. Hence, anthropogenic component of SSY is that quantity of deposits which has additionally arrived or has not arrived with runoff into a river network above a hydrological post during period T_2 (and/or T_3) due to activization of human activity within river basin during given period. A human activity can be rather various: deforestation, cultivation, a change of structure of crop rotations, expansion and intensification of pastures, mining operations in valley bottoms, grassing, expansion of afforestations, antierosive actions, non-using of cultivated lands due to difficult economic problems in regions, creation of water reservoirs and ponds, etc.

The *anthropogenic component* in changed SSY of period T_2 or T_3 – $\Delta A(T_{2\text{ or }3})$ – is a difference between average actual SSY-amount for these period ($R_{av}(T_2)$ or $R_{av}(T_3)$) and its average hydro-climatic (hypothetical) component ($r_{av}(T_2)$ or $r_{av}(T_3)$):

$$\Delta A(T_{2\text{ or }3}) = R_{av}(T_{2\text{ or }3}) - r_{av}(T_{2\text{ or }3}) \qquad (4)$$

If $\Delta A > 0$ then a human activity is directed to increase of SSY, if $\Delta A < 0$ then – to reduction of it.

Similar (in essence) approach to allocation of anthropogenic component of SSY, but already in scale of all history of economic development of river basins of the Earth, have been applied by A.P. Dedkov and V.I. Mozzherin [2, 16], who used the ergodic principle, that is transformation of spatial laws into temporal ones (allocation of three categories of river basins with different degree of transformation of natural landscapes in them).

Theoretically, it is possible to allocate the 13 probable scenarios (I–XIII) of SSY-changes in connection with trends of changes of river water discharge with isolation of two periods (figure). These scenarios reflect a various parities between natural (hydro-climatic) and anthropogenic components in a *changed SSY* (ΔR) which can be defined as:

$$\Delta R\ (T_{2\text{ or }3}) = R_{av}(T_{2\text{ or }3}) - R_{av}(T_1), \qquad (5)$$

If $\Delta R < 0$ then a reduction of SSY from period T_1 to period T_2 or T_3 is marked, if $\Delta R > 0$ then an increase of SSY is marked (its "superstructure").

The scenarios I, II and III are purely hydro-climatic, because river SSY-changes at them occur without participation of a human activity: from river basins with still not transformed natural landscapes to river basins completely occupied with bad lands where agriculture does not already take place. The special cases of scenarios III and XII are a termination of SSY during the second period (where $R_{av}(T_2) = 0$) due to a termination of water discharge, connecting with river degradation (it concerns, mainly, small rivers) in conditions of a drainage of soil and ground waters, feeding the rivers, and excessive sedimentation along the river channels. The sources of such rivers are displaced downstream, settling down at exits of deeper ground waters, weakly transformed by drainage. Such picture is widely observed, for example, there where men reduced the forest areas and ploughed up the lands, changing, thereby, a ratio between the surface and underground waters [17, 18]. It is natural that in these cases a runoff and SSY are observed during a snow melting and/or rains but then such rivers already stop to be by itself, because from the constant water streams (actually the rivers) it turns to the temporary water streams, and its former valleys become the dry valleys.

4.4a. Definition of structure of the changed SSY (ΔR) during period T_2 or T_3: a portion of natural (hydro-climatic) component in changed SSY – ωr ($T_{2 \text{ or } 3}$) and portion of anthropogenic component – ωA ($T_{2 \text{ or } 3}$). Depending on the scenario of directed SSY-changes the calculation of specified portions is made as follows (table).

If the portion of one of these components makes 33–50 % it is possible to speak about its moderate influence on the changed SSY between the allocated periods, if 51–66 % – about prevailing, 67–90 % – about dominating, 91–100 % – about overwhelming influence.

4.4b. Definition of structure of the actual SSY – R_{av} ($T_{2 \text{ or } 3}$) – during the period T_2 (and/or T_3): the portion of natural (hydro-climatic) component – ∂r ($T_{2 \text{ or } 3}$) and the portion of anthropogenic component – ∂A ($T_{2 \text{ or } 3}$) (table).

5. Last stage is analysis of reasons of the modern tendencies of erosion intensity and SSY-changes in each river basin.

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TABLE DEFINITION OF STRUCTURE OF CHANGED (ΔR) AND ACTUAL (R_{av}) SSY

<table>
<tr><th>Probable scenarios (see figure)</th><th>Structure of ΔR for period T_2, %</th><th>Structure of R_{av} for period T_2, %</th></tr>
<tr><td colspan="3">Hydro-climatical scenarios</td></tr>
<tr><td>I</td><td>$\omega r = 100$
$\omega A = 0$</td><td rowspan="3">$\partial r = 100$
$\partial A = 0$</td></tr>
<tr><td>II</td><td>—</td></tr>
<tr><td>III</td><td>$\omega r = 100$
$\omega A = 0$</td></tr>
<tr><td colspan="3">Anthropogenic–hydro-climatical scenarios</td></tr>
<tr><td>IV</td><td>$\omega r = [\Delta r/\Delta R]\times100$
$\omega A = 100 - \omega r$</td><td>$\partial r = [r_{av}/R_{av}]\times100$
$\partial A = 100 - \partial r$</td></tr>
<tr><td>V</td><td>$\omega r = 100$
$\omega A = 0$</td><td>$\partial r = 100$
$\partial A = 0$</td></tr>
<tr><td>VI</td><td rowspan="2">$\omega r = 0$
$\omega A = 100$</td><td rowspan="2">$\partial r = [r_{av}/R_{av}]\times100$
$\partial A = 100 - \partial r$</td></tr>
<tr><td>VII</td></tr>
<tr><td>VIII</td><td>—</td><td>$\partial r = 100$
$\partial A = 0$</td></tr>
<tr><td>IX</td><td>—</td><td>$\partial r = [r_{av}/R_{av}]\times100$
$\partial A = 100 - \partial r$</td></tr>
<tr><td>X</td><td rowspan="2">$\omega r = 0$
$\omega A = 100$</td><td rowspan="3">$\partial r = 100$
$\partial A = 0$</td></tr>
<tr><td>XI</td></tr>
<tr><td>XII</td><td>$\omega r = [\Delta r/\Delta R]\times100$
$\omega A = 100 - \omega r$</td></tr>
<tr><td>XIII</td><td>$\omega r = 100$
$\omega A = 0$</td><td>$\partial r = [r_{av}/R_{av}]\times100$
$\partial A = 100 - \partial r$</td></tr>
</table>

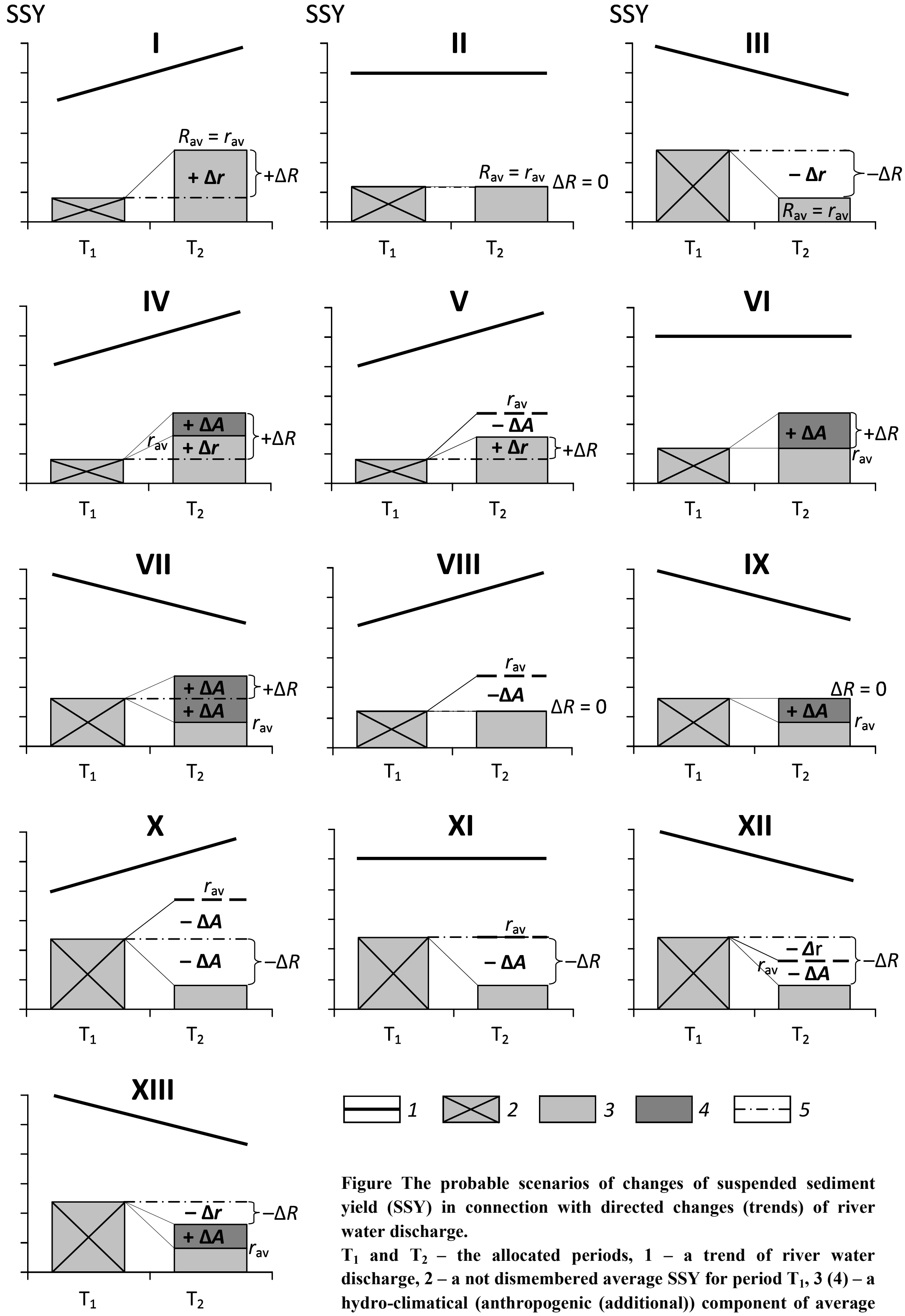

Figure The probable scenarios of changes of suspended sediment yield (SSY) in connection with directed changes (trends) of river water discharge.

T_1 and T_2 – the allocated periods, 1 – a trend of river water discharge, 2 – a not dismembered average SSY for period T_1, 3 (4) – a hydro-climatical (anthropogenic (additional)) component of average SSY for period T_2, 5 – a level of not changed SSY for period T_2.